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Scientific Framework for a Comprehensive Assessment of Tribal Water Resources in Western Washington

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U.S. Department of the Interior
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Scientific Framework for a Comprehensive Assessment of Tribal Water Resources in Western Washington

By Christopher P. Konrad

Abstract

Judicious management of water resources and protection of Tribal water rights requires information about the quantity and quality of water available in western Washington, the quantity of water needed by Tribes for current and future out-of-stream uses, and the quantity of water needed for salmon restoration and protection. A framework for a comprehensive assessment of Tribal water resources in western Washington would produce scientific information on water resources that could be used to support various Tribal management, administrative, and legal activities.

The assessment would evaluate water resources with regard to three research goals:

1. Quantity, timing, and location of water available for all in-stream and out-of-stream uses;

2. Quantity and quality of water needed to satisfy current and future out-of-stream uses by Tribes in western Washington; and

3. Quantity, quality, location, and timing of streamflow necessary to restore and protect aquatic ecosystems so that they support sustainable populations of harvestable fish.

Past and future changes in water use, flood control, land drainage, land cover, and climate require that the assessment have both historical and future perspectives on water resources in the region. The information needs of resource managers should ultimately guide implementation of the framework including the level of detail.

Introduction

Water resources are essential for people and ecosystems in western Washington but are limited by physical availability and competing uses. Judicious management of water resources in the region requires a comprehensive understanding of water resources to identify the full consequences of water management decisions. Although Native American Tribes, Federal, State, and local government monitor and assess water resources, the information generally has not been integrated across the region nor is much of it easily accessible to water-resources managers. The western Washington Tribal members of the Northwest Indian Fisheries Commission (NWIFC) requested that the U.S. Geological Survey (USGS) develop a scientific framework for a comprehensive assessment of water resources in western Washington. The assessment would provide a scientific basis for Tribal water-resources management including water claims and protection of Tribal treaty and reserved water rights by evaluating unimpaired water availability, out-of-stream uses of water by Tribal and non-Tribal parties, and water requirements for ecosystems in western Washington.

The purpose of this report is to outline a framework for the assessment. This framework describes in general terms a comprehensive assessment of Tribal water resources in western Washington. The assessment would evaluate water resources with regard to three research goals:

1. Quantity, timing, and location of water available for all in-stream and out-of-stream uses;

2. Quantity and quality of water needed to satisfy current and future out-of-stream uses by Tribes in western Washington; and

3. Quantity, quality, location, and timing of streamflow necessary to restore and protect aquatic ecosystems so that they support sustainable populations of harvestable fish.

This framework was developed to retain flexibility for the approach and implementation of the water-resources assessment. Flexibility is important because individual Tribes may have distinct issues and policies related to water resources and they may choose particular assessment methods that suit their needs in some situations. As such, the framework does not prescribe specific methods nor is it intended as a detailed technical guidance document for implementing the assessment of Tribal water resources in western Washington. Moreover, new methods for assessing water resources can be incorporated or developed in the future as needs arise.

Implementation of the assessment generally is outside of the scope of the framework. It would not be implemented by a single investigation because it covers a wide range of activities including:

- Compilation of existing information on water resources in western Washington;
- On-going monitoring of water resources;
- Collaboration among Tribes to collect and manage information; and
- Coordination among Tribes to standardize information collection and management (for example, through training, consultation among Tribes to share information and analysis, and planning of future monitoring and research).

The assessment could be initiated at a regional scale using existing data through the NWIFC and through coordinated efforts of multiple Tribes, but individual Tribes may choose different approaches that reflect their unique situations and their policy or management decisions to address specific issues or stream reaches of interest as they see fit. The assessment could extend the results of such investigations by individual Tribes to the larger region where appropriate. In addition, there are opportunities for cooperative efforts between Tribes and non-Tribal organizations to ensure the consistency, quality, and continuity of water-resources information across western Washington.

Description of Western Washington

The assessment of Tribal water resources would extend from the Cascade Range to the Olympic Peninsula, and includes southwestern Washington, parts of Canada that drain to western Washington, and nearshore areas of Puget Sound and the Pacific coast (fig. 1). Subsequent references to western Washington include all these areas. The region includes lowland areas along the coast of the Pacific Ocean and Puget Sound and mountainous areas in the Olympic and Cascade Ranges. The mountain ranges were formed through tectonic and volcanic processes. During the Pleistocene, a lobe of the Cordilleran ice sheet covered lowland areas around Puget Sound while mountain valleys were filled with alpine glaciers. Western Washington has a humid, maritime climate with relatively dry summers and wet winters. Precipitation generally increases with elevation and ranges from about 1 m/yr of rain in lowland areas and to more than 3 m/yr of snow-water equivalent in the mountains. Temperatures are moderated by the proximity of the land to the Pacific Ocean and Puget Sound. Land uses in the region include urban (residential, commercial, and industrial) and agriculture in lowland areas and silviculture in the lowlands and low-elevation mountains.

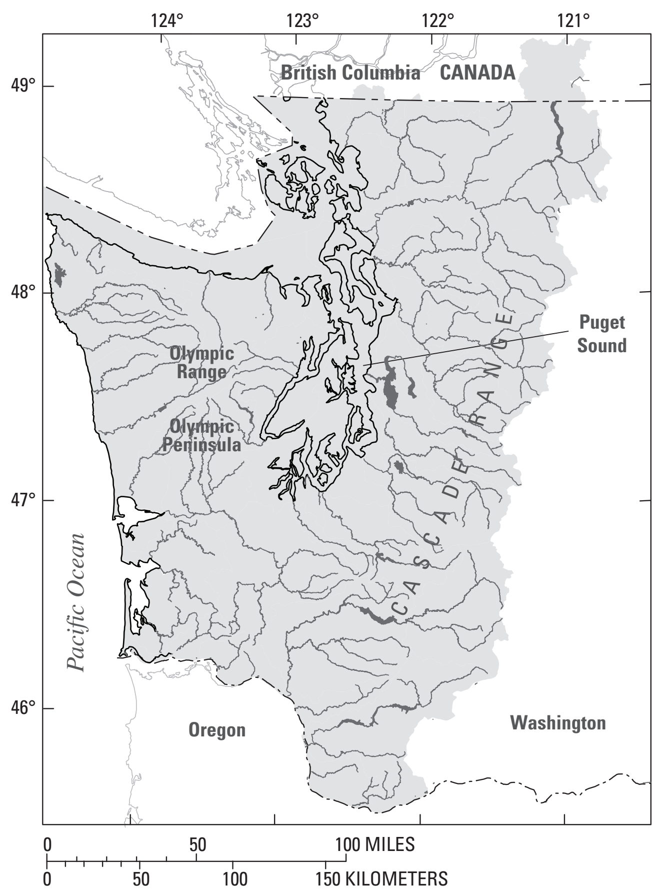

Figure 1. Western Washington and adjacent areas.

Scientific Framework for a Comprehensive Assessment

The Tribal Water Resources Group of the NWIFC identified the need for a comprehensive assessment of water resources in western Washington as a basis to inform management of those resources (Hollowed and others, written commun., 2004). Judicious management of water resources and protection of Tribal rights requires information about the quantity and quality of water available in western Washington, the quantity of water needed by Tribes for current and future out-of-stream uses, and the quantity of water needed for salmon restoration and protection. The assessment would produce scientific information on water resources that could be used to support various Tribal management, administrative, and legal activities including:

- Establishment of instream flows to sustain viable and harvestable populations of fish;
- Identification of limiting factors for salmon recovery;
- Evaluation and quantification of water resources on and off Tribal lands;
- Development of on-reservation ground- and surface-water supplies;
- Protection of existing ground- and surface-water supplies and Tribal reserved rights for water resources;
- Review and evaluation of administrative decisions (for example, proposed water permits and instream flows) and project proposals on and off reservations; and
- Participation in Federal, State, and local planning processes for water-quantity and water-quality management (for example, Total Maximum Daily Load planning, Washington State watershed planning under Engrossed Substitute House Bill 2514, and conjunctive use projects).

Water resources in western Washington have been the subject of extensive scientific investigation since the late 19th century by Tribal, Federal, State, and local government agencies, public utilities, and private interests. Despite this recent history of investigations, much of the data collected are not readily available to Tribal water resources managers. Many of the investigations were motivated by a specific local concern, such as siting a dam to generate hydroelectricity, determining instream flows for a specific reach of a river, or assessing water use for a municipality or water system. Although some information about water sources, availability, and out-of-stream and instream uses has been integrated for specific basins or subbasins, water-resources information has not been compiled on a comprehensive basis for western Washington. As part of the Tribal water resources assessment, existing information would be compiled for the region on water sources, quality, and uses and existing or new information systems would be used so that the information is readily available to Tribal water resources managers.

A compilation of existing information also would provide a basis for identifying information gaps and approaches for filling them. Information gaps reflect the large and diverse geography of the region, the various time-scales of information ranging from instantaneous flows to decadal climate variability, and the limits on the scientific understanding of river ecosystems and the regional hydrosystems that support them. Some types of information will not be available on a comprehensive temporal or spatial basis for all western Washington. For example, ground-water levels are available or may be easily obtained where there are existing wells, but there are times when water levels were not recorded and locations where there are no wells to monitor water levels. In other cases, additional information may be required to develop a component of the assessment. For example, a relation between precipitation and runoff may have to be developed for areas where streamflow data are not available. Ecological relations that demonstrate the role of streamflow in ecosystems, such as the streamflow necessary for formation of pool and side-channel habitats, will be a particular area where additional information will be needed. Thus, a primary objective of the assessment will be to identify areas of western Washington where additional monitoring, surveys, or focused studies are needed to improve the initial characterization of water resources in western Washington.

In western Washington, climatic changes (Vaccaro, 2002; Mote, 2003; Mote and others, 2003) and urban development (Konrad and Booth, 2002; Konrad and others, 2005) are having and will likely continue to have profound effects on water resources and aquatic ecosystems. The changing status and trends in water resources require that information compiled as part of the assessment is regularly updated and the implications of persistent changes are projected. Although some effects (such as lower snowpack, earlier runoff, increased winter flooding, and reduced baseflow in spring) can be anticipated, there is little precedent for quantitative projections of these and other unanticipated effects of changing climate and land cover at a regional scale. The status of water resources in western Washington must be updated regularly as part of the assessment. To achieve this goal, the assessment must include on-going monitoring, allow new information to be easily incorporated as it becomes available, and project potential future conditions of water resources in the region. The scientific framework identifies specific ways to address climate change and urban development for each of the three goals.

Goal 1. Assessment of Water Availability

The quantity and quality of water physically available for various instream and out-of-stream uses impose limits on any Tribal or non-Tribal water-resources planning and management decisions. Water availability also dictates how past, current, and future uses impact each other. The comprehensive assessment of water resources in western Washington would begin by accounting for all sources of fresh water in the region including streamflow, ground water, lake and reservoir storage, and snow and ice. Each source of water should be assessed because: the sources are interdependent; they may serve a unique role in satisfying some uses; and they may respond differently to climate and land-uses changes. Because the sources of water are interdependent, as in the case of a river recharging an aquifer, management activities impacting one source of water may have consequences on other sources. These consequences may have a negative impact when ground-water pumping reducing streamflow in nearby rivers or a positive impact when ground water and surface waters are used conjunctively to limit ecological impacts. The links between sources of water and uses is particularly important for ecosystems. For example, ground-water discharge to rivers and estuaries may be important for regulating water-quality characteristics such as temperature, nutrients, and salinity. The sensitivity of sources to changes in climate and land use will have important implications on the future status of these sources and, as a result, priorities for monitoring water resources.

The location, timing, and quantity of water from these sources establish the physical availability of water for in-stream and out-of-stream uses. The portion of these water resources that is legally available for Tribal uses is beyond the scope of the assessment. Current uses (particularly consumptive uses), interbasin transfers, and intrabasin transfers (including irrigation systems that divert surface water and return a portion to ground water or divert from a river at one location and return water to another location of the river), however, could be a component of the assessment. Water quality is critical to its in-stream and out-of-stream uses, so the assessment of water availability should incorporate water-quality characteristics in addition to water quantity.

Water Balance Approach

Water balances provide the basis for assessing the sources of water for a region of interest (Dunne and Leopold, 1978). A water balance expresses the conservation of mass of water for a specified region where the input of water to the region is equal to the sum of outputs from the region and any changes in storage in the region. The input term in a water balance is precipitation (PPT) except in cases where water is transferred from outside of the region of interest (for example, an interbasin transfer). The output terms in a water balance are evapotranspiration (ET), streamflow or runoff (Q_{sw}), and ground-water flow (Q_{gw}). Water can be stored in surface waters (SW) including lakes, other wetlands, and surface-water reservoirs, the snow pack where it is expressed as snow water equivalent (SWE), the ground-water system (GW), soil moisture (SM), and in glacial ice (G). A water balance for a given period of time can be represented mathematically by:

$$\begin{aligned} PPT - (ET + Q_{sw} - Q_{gw}) \\ = \Delta(SWE + SW + GW + SM + G), \end{aligned} \qquad (1)$$

where $\Delta(SWE + SW + GW + SM + G)$ represents either a positive or negative change in storage for the period, and each term is expressed either as a volume of water for the period or an equivalent depth of water over the region’s area.

The exact quantities represented by the terms in equation (1) vary depending on the area of interest. For example, Q_{sw} could represent streamflow at the outlet of a river basin or runoff from a hillslope. Likewise, Q_{gw} can represent either recharge, in which case GW represents soil-moisture content, or ground-water flow out of some region of an aquifer, in which case GW represents soil moisture content and aquifer storage. For shoreline catchments in western Washington, both Q_{sw} and Q_{gw} would include diffuse flow into the Pacific Ocean, Puget Sound, or other estuaries. Use of water is not explicitly accounted for in equation (1) and may be represented either by its effects on each term (for example, irrigation using ground water would produce a negative ΔGW term and an increase in ET) or though additional terms in the equation.

The terms of a water balance can be derived from direct measurements, statistical distributions, empirical relations, or process models (Langbein and others, 1949; Thornwaite and others, 1957; Eagleson, 1978; Barlow and others, 2002; Hay and McCabe, 2002). There are numerous recent examples for western Washington (for example, Bauer and Mastin, 1997; Burges and others, 1998; Vaccaro and others, 1998; Dinicola, 2001). A water balance could be constructed simply by applying equation 1 to selected points using existing maps of precipitation, ET , and runoff, though the spatial and temporal resolution would be coarse (for example, mean monthly water balance for a stream basin). The approach could be refined by using empirical or theoretical functions for ET (Vorosmarty and others, 1998) and calculating ground-water flow from baseflow recession in rivers (Rutledge, 1998). A spatially distributed water balance could be constructed using a geographic information system (GIS) to automate calculations. A hydrologic simulation model could be used to construct a more detailed version of the water balance that would resolve spatial and temporal differences in sources of water. A hydrologic simulation model would increase the flexibility of potential applications of the water balance such as to assess either historical or future alternatives where climate, land cover, and water use vary from current conditions.

The time period for the water balance must be specified and will affect the results (Dunne and Leopold, 1978). For example, monthly water balances in western Washington will highlight the uneven, seasonal distributions of both the flux and storage terms that would be averaged in an annual water balance. Because uses of water typically vary during the year and most basins in western Washington do not have the capacity to store a large fraction of the water available during the wet season, monthly water balances are necessary to identify periods of lowest water availability. Water balances can be constructed for different conditions (for example, annual water balances could be constructed for both a wet year and a dry year). In addition to the monthly water balance, flood statistics (peaks and volumes with a given annual probability) could be calculated.

The spatial resolution of a water balance can range from river basins where each term of the water balance is calculated for a whole basin (as described by Hay and McCabe, 2002) to headwater catchments (for example, Burges and others, 1998) or individual cells of a grid representing a landscape (Haddeland and others, 2002). In western Washington, a water balance can be applied to catchments without defined streams that drain, for example, to Puget Sound. In this case, Q_{sw} and Q_{gw} represent hillslope runoff and ground-water flow into the near shore and the primary storage terms are soil moisture and, potentially, vegetation.

A spatially distributed water balance will be more useful than a basin-scale water balance for assessing water sources in western Washington because in-stream and out-of-stream uses typically depend on location. For example, a spatially distributed water balance could be used to calculate water sources and potential water availability for each of the river segments in the Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP). The integration of water availability data with stream habitat and fish distribution data would facilitate the analysis of hydro-biologic relations (discussed in Goal 3) and would allow proposed uses of water to be assessed in terms of geographically specific impacts on stream habitat and fish. Likewise, the results of the water balance should be easily integrated with existing State or Federal water-quality information systems to allow more detailed examination of water availability for specific instream and out-of-stream uses.

Developing Water Balances

Any approach for developing a water balance from the direct solution of equation (1) or the development of a more detailed simulation model requires much of the same information, which will vary in terms of its availability, resolution, and quality. Spatially distributed values of PPT, ET, and Q_{gw} are available for western Washington (Farnsworth and others, 1982; Vaccaro and others, 1998; Spatial Climate Analysis Service, 2005), although their accuracy and precision may be limited. Temporal distribution of precipitation at a monthly or even daily scale are available for precipitation, but not for ET or ground-water flow. The spatial and temporal resolutions of available ET and Q_{gw} data, in particular, are fairly coarse. Q_{sw} and Q_{gw} can be calculated on a spatially distributed basis with additional information (topography, solar radiation, temperature, vegetation cover, soils, geology, and ground-water levels).

Daily streamflow information is available at selected sites for many rivers and streams in the region from the USGS, Washington State Department of Ecology, and some local governments. Streamflow information can be extrapolated to other areas or records can be extended to different time periods using statistical techniques (Helsel and Hirsch, 1991) or empirical relations based on climate and basin geomorphology (Tangborn and Rasmussen, 1976; Mosley and McKerchar, 1993). Hay and McCabe (2002) outline an approach for estimating monthly runoff that requires precipitation, streamflow, temperature, and topographic data that generally are available for western Washington. This approach incorporates methods for calculating evapotranspiration (ET) and soil-moisture storage and represents a simple hydrologic model that would be implemented using a GIS.

More sophisticated hydrologic simulation models can be used to calculate each term in the water balance. For example, the Distributed Hydrologic Soil and Vegetation Model (DHSVM) has been applied to much of western Washington to simulate streamflow from climatic information (URL: http://hydromet.atmos.washington.edu/, accessed October

2005). Hydrologic simulation models offer more flexibility in terms of the temporal scale of analysis and have already developed relations for coupling hydrologic processes. For example, ET is related to wind, solar radiation, air temperature, humidity, and the availability of water in the soil. Simulation models generally will require the same types of underlying data (for example, precipitation, solar radiation, wind, temperature, soils/geology, topography, and drainage networks) as simpler GIS-based approaches, though each model has specific input requirements in terms of both content and format. A model can be calibrated to a specific site or basin to increase the accuracy of its results. Simulated results for a specific basin also may be extrapolated and applied to areas lacking hydrologic data, though generally a model would require recalibration if it is applied to a new area. A simulation model, however, will not necessarily be more accurate than a simpler GIS-based water balance.

Water-Balance Alternatives

A water balance can be used to compare water availability under different conditions or alternatives. Four water-balance alternatives would be useful for a Tribal water-resources assessment:

(1) Current condition that represents conditions as they would actually be measured or observed with existing land and water uses in place;

(2) A historical condition that represents land cover and drainage networks at the time that treaties between Native American Tribes and the United States Government were signed;

(3) A condition that represents current land uses (vegetation, impervious surface) including drainage networks (agricultural drains, road ditches, storm sewers, filled wetlands, rivers with levees/dikes) but not the effects of water use (diversions, ground-water pumping, and river regulation/storage for flood control, energy production, or navigation); and

(4) A future alternative that accounts for likely or potential changes in climate, land use, and water management.

Estimates of water availability under alternatives 2, 3, and 4 will necessarily have higher uncertainty than the estimates for alternative 1 because of limited data for model calibration and their relatively high uncertainty.

A water balance can produce estimated ranges of streamflow, ground-water recharge and aquifer storage at locations throughout western Washington for each alternative. Each alternative would likely include a range of wet and dry years and resolve water availability at a seasonal or monthly time scale. The results from the alternatives could be loaded into a GIS database, which would require calculating and entering water-balance information for all alternatives and places of interest. Alternatively, a web-based GIS tool could allow alternatives to be run in real-time for the location of interest. This approach might not be compatible or easily implemented with all hydrologic simulation models, but it would allows results of the alternatives from a GIS-based water balance to be updated as source data or hydrologic algorithms are revised. The USGS program StreamStats (U.S. Geological Survey, 2005) provides one example of a web-based, GIS tool that allows a user graphically to select a point or reach of interest and returns hydrologic information of interest. This type of a tool could allow easy access to information on water resources in western Washington.

Scientific Contributions

The assessment of water availability would contribute to the scientific understanding of western Washington hydrology through: (1) development of geographically comprehensive information on water resources that incorporates existing and new hydroclimatic data to the extent possible; and (2) identification of information gaps.

GIS coverages of precipitation for the region could be verified and revised, if necessary, with data from precipitation gages or from the water balance itself (for example, Adam and others, in press). Spatially distributed values of ET could be estimated for the region using empirical equations or models that account for effects of vegetation type, solar radiation, soil water content, winds, and temperature and incorporates relevant plot-scale information (Fritschen and others, 1977; Unsworth and others, 2004). A GIS coverage of ground-water availability could be developed based on existing hydrogeologic studies and geologic mapping for the region. Regional streamflow relations could be evaluated and refined with available streamflow measurements including information on ground-water and surface-water exchanges. Existing web-based tools for obtaining water-resources information such as the USGS National Water Information System and StreamStats provide models for the information system that would make water-resources information easily accessible and able to be integrated with other information or simulation models.

A water balance may not be very precise in many locations because of a lack of existing data, but it would give water-resources managers an initial range of the likely physical availability of water to compare to current and proposed uses and target streamflows (for example, Washington State regulatory baseflows). The information could be used to assess historical water sources, the consequences of land use (which can alter ET, streamflow, ground-water flow relations) and water-resources development, and the potential effects of proposed activities (for example, additional storage or land cover changes). Hydrologic information compiled on a regional basis for western Washington would enable Tribal water-resources managers to respond quickly to new project proposals that affect water resources—particularly numerous smaller projects that may be difficult to analyze effectively on an ad hoc basis. Tribes also would be able to coordinate their assessments of water resources, eliminating potentially redundant efforts. Tribal water-resource managers could use regionally comprehensive information on water sources and availability to understand the broader context of local projects and to address regional concerns at the site scale.

In addition to developing a comprehensive base of hydrologic information for western Washington, the assessment will identify information gaps that limit the certainty of the water balance along with approaches for filling those gaps including the on-going need for information about water resources. For example, continuous streamflow gaging in certain streams or miscellaneous streamflow measurements during critical periods (for example, flood events or drought periods) could be used to provide streamflow values directly for the water balance, to develop regional relations for estimating streamflow in ungaged streams, or to calibrate a runoff model. Seepage runs, which are sequences of nearly simultaneous streamflow measurements made along a river, could be used to document ground-water and surface-water interactions that are important particularly to low-flow conditions in streams. Ground-water level monitoring and aquifer testing could be used to improve estimates of recharge and aquifer storage in areas where these aquifer characteristics are uncertain. Geochemistry of ground water may provide evidence about its age and an indication of its quality for uses. The age of ground water is important to distinguish whether it represents a recent and renewable resource or an artifact from ancient time that is depleted as it is used. Information gaps also can be filled by using technical analyses rather than additional data collection. Hydrologic simulations models that have been calibrated for the region could be chronicled and analyzed to extend their results, if only in a general sense, to areas where such models have not been applied.

There will be an ongoing need for updated hydrologic information for the region because of changes in the climate and land use. Thus, the water availability assessment will address not only current information gaps but needs for continued monitoring and analyses to account for future changes.

Tasks

1. Determine geographic extent (western Washington), spatial scale (basin, subbasin, reach, cell), and temporal scale (day to decades) of water balance.
2. Identify which approaches (empirical relations, hydrologic simulation model) may be used for the assessment.
3. Develop specifications for water-balance information including how information can be accessed (web) and its format (compatible with hydrologic models), assure consistency or integration with other information systems (NWIS, SSHIAP, STORET, StreamStats).
4. Compile existing hydro-climatic information (precipitation, air temperature, solar radiation, wind, evapotranspiration, streamflow, ground-water levels) and supporting physiographic (surficial geology and soils, aquifer extents and thicknesses, topography, river channel networks, land cover) and anthropic (land use, drainage systems, roads, dams, diversions, canals) information.
5. Identify gaps (spatial and temporal) in coverages and assess whether existing information can be extended or interpolated to fill gaps or if additional information must be collected. The most extensive gaps are likely to be in evapotranspiration and ground-water information for current conditions and in all types of information for historical conditions.
6. Implement water-availability assessment.

Goal 2. Assessment of Water for Out-of-Stream Tribal Uses

Tribes in western Washington require water to support domestic, commercial, municipal, industrial, and agricultural out-of-stream uses. The objective of the assessment with regard to this goal would be to quantify water needed to support existing and future out-of-stream uses by Tribes on and off reservations. The estimates would not necessarily be limited to existing legal standards for reserved water rights (for example, “practicably irrigable acreage” and “homeland purposes”).

Approach

A regional-scale assessment of out-of-stream Tribal water use could be implemented following the approach used by the USGS to assess State water use. The existing USGS State Water Use Data System (SWUDS) might be adapted to store information about out-of-stream Tribal uses in western Washington. Water-use information systems could be modified to include information about water quality or treatment before and after uses or to allow links to existing information on water quality. More detailed assessments that include projected water use would depend on the availability of site-specific water-use information, Tribal policies and management decisions regarding future uses, and assumptions about future growth of water uses. Because of variation in available information and policies among Tribes, Tribes might not proceed with consistent assessments of out-of-stream uses. The current and future demand for water would be quantified by major use categories (for example, domestic, industrial, and irrigation). More detailed assessments could include uses according to water purveyors and supplies (for example, domestic wells) or specific crops, industries, and businesses. Because of the uncertainty of future water use, any use projections should include a range of future use and an estimate of the uncertainty of the projection.

Available Data

The assessment could be based on available data for water use on reservations, census information, published values of per capita water demand for residential use in western Washington, crop-specific irrigation rates, soil classification, and rates of commercial and industrial uses. General methods for collecting water-use data are described by Templin and others (1991). Lane (2004) estimated per capita domestic uses, irrigation uses, and industrial uses by county in Washington for 2000 that could be applied where water-use data are not available. Information about the quality of water currently used for specific uses and the fate and quality of water after it is used also may be important to incorporate in the assessment. In many cases, specific quantities and locations of uses may not be available, in which case either these data need to be collected or estimated. Such data can be aggregated where uses and sources should not be disclosed (for example, public water supplies) or where disclosure would discourage users from providing information about uses. Current rates of water use could be used to estimate or project future water use and could be compared to projections based on per capita water use and population projections.

Tasks

1. Compile available data on Tribal water use, population, soils, and develop a geographic database of water uses.
2. Develop a new or modify an existing information system for estimating and projecting Tribal water use.
3. Calculate current Tribal uses and project future Tribal uses.

Goal 3. Assessment of Water Requirements for Aquatic Ecosystems

Aquatic ecosystems in western Washington from alpine lakes in the Olympics and Cascade Ranges to near-shore habitats of Puget Sound depend on fresh water for many ecological functions. Ground-water and surface-water inflows to rivers, lakes, other freshwater wetlands, and estuaries are essential to the survival and recovery of salmon in western Washington. The need for fresh water in western Washington is defined by the location, timing, and quality of streamflow and ground water necessary to support ecological functions in aquatic ecosystems. An understanding of the ecological functions of water, including their sensitivity to changes in either the quantity or quality of streamflow and ground water, is the first step toward establishing adequate requirements to restore and protect aquatic ecosystems in western Washington. The primary objectives of the assessment with regard to this goal would be to (1) identify the most important ecological functions of streamflow and ground-water discharge; (2) map the geographic extent of these functions in river networks and near-shore regions; and (3) assess how those functions depend on or are sensitive to changes in flow rates and water quality.

Approach

Many approaches are available for determining water requirements of rivers but not for other aquatic ecosystems. This discussion focuses on approaches for determining streamflow requirements with the acknowledgment that these approaches may not be extended to other types of aquatic ecosystems. As a result, new approaches will be needed to assess freshwater requirements of lakes, other freshwater wetlands, estuaries, and near-shore habitats, but may still be addressed within the framework presented in this report. Likewise, riparian habitats depend on streamflow and ground water and serve an important role in aquatic ecosystems. Thus, water requirements for riparian areas would be another important component of the assessment.

The approaches for determining water requirements for rivers vary with respect to their focus, analytical basis, and degree to which streamflow requirements are quantified. Some approaches were not developed to quantify streamflow requirements (for example, hydrologic and hydraulic models), but nonetheless can be adapted to this task. The approaches can be grouped according to their general focus: (1) changes in streamflow patterns from a historical or normative state; (2) ecological processes including, but not limited to, functions of water in rivers; and (3) specific habitat or life-history requirements of salmon (table 1). Each approach offers distinct advantages but also has limitations. These limitations are the focus of current research (Gore and others, 2001; Greene and Beechie, 2004) which would likely be a necessary aspect of the Tribal water-resources assessment.

Streamflow requirements can be based on historical standards of unregulated streamflow. Historical standards for streamflow can be developed from statistical analyses of streamflow records (for example, Richter and others, 1996; Lins and Slack, 1999), categorical systems for classifying streamflow regimes (for example, Poff and Ward, 1989), and models of streamflow, ground-water flow, and open-channel hydraulic processes (table 1). These approaches rely on historical records of unimpaired streamflow or current records of unimpaired streamflow from reference systems to develop standards for current streamflow at site of interest.

Table 1. Approaches for establishing the water requirements of aquatic ecosystems.

Basis for water requirements	Empirical approaches	Categorical approaches	Process-based approaches
Historical or normative streamflow	Hydrologic trends (Lins and Slack, 1999 ; Konrad and Booth, 2002) Normative patterns (Richter and others, 1996)	Multivariate hydrologic regimes (Poff and Ward, 1989)	Hydrologic and hydraulic simulation models (Jacobson and others, 2004; Storck and others, 1998)
Ecosystem components/ processes	Hydrologic regime classes (Wood and others, 2001)	Watershed analysis (Washington State Department of Natural Resources, 2005)	Fluvial landscapes (Ward and others, 2001)
Salmon habitat or population	Instream Flow Incremental Methodology (Bovee, 1982)	Expert systems (Washington State Conservation Commission, 2005; Mobrand Biometrics, 2005)	Life-history models (Bartholow and others, 1993; Green and Beechie, 2004)

Historical standards for streamflow requirements have a number of potential limitations. They typically are developed from and applied to a specific site with a stream gage and, thus, may not account for spatial extent and connectivity of aquatic habitats. They may not account for other anthropogenic changes in the ecosystem that affect how water functions. For example, changes in channel networks and morphology along with streamflow regulate the depth, velocity, and wetted area of aquatic habitat. Likewise, streamflow standards derived solely from hydrologic analysis may not address the role of streamflow in all of its ecological functions including water quality (temperature and sedimentation) or habitat formation. Finally, historical or normative standards do not account for the incremental effects of flow regulation or impairment, thus, different levels of streamflow impairment in assessing trade-offs between instream and out-of-stream uses of water may be difficult to evaluate. As a result of these limitations, precise streamflow requirements for maintaining river ecosystems based on historical or normative standards may be difficult to establish.

Because streamflow requirements derived solely from hydrologic analysis do not establish clear ecological benefits, they may be difficult to implement within the current administrative system for allocating water to beneficial uses. As an alternative, streamflow requirements can be developed to restore and protect ecological functions in rivers and potentially lakes, other freshwater wetlands, and estuaries. In this case, the link between ecological function and hydrologic processes or conditions must be established (table 2).

Table 2. Examples of hydrologic processes and conditions needed to support ecological functions with an emphasis on requirements for salmon.

Ecological functions	Hydrologic processes or conditions
Create aquatic habitats (succession)	In-channel sediment transport (erosion and deposition) Wood recruitment Channel evolution (migration/avulsion, side channel creation)
Maintain aquatic habitats (common requirements for all fresh-water life stages)	Water temperature Water chemistry (DO, contaminants, pH) Suspended sediment Sediment supply (upstream/in-channel) and sediment transport capacity
Create riparian habitats (succession)	Overbank sediment transport (erosion and deposition) Channel evolution (migration/avulsion, side channel creation) Seed/vegetation dispersal to unvegetated surfaces Propagate young plants
Maintain riparian habitats	Floodplain inundation Depth to ground water/soil moisture Nutrient storage and processing
Maintain adult salmon migration corridors	Depth and velocity in migration corridors Holding areas Freshets Connectivity between estuary and spawning habitat
Maintain salmon spawning and incubation habitat	Gravel, selective transport of fine sediment over redds Riffles, bars, channel margins GW-SW connectivity (intragravel or hyporheic flow) Continuous flow over redds during incubation
Maintain juvenile rearing for salmon	Depth and velocity Cover Connectivity between low velocity habitat (side channels, pools) and food sources
Maintain smolt migration corridors	Depth and velocity Freshets Connectivity between rearing habitat and estuary
Support juvenile salmon food base	Water chemistry (nutrients, contaminants, DO, pH) Suspended sediment Substrate Channel forms

A number of approaches have been developed to identify or account for ecological functions of streamflow (for example, Poff and others, 1997; Trush and others, 2000; Wood and others, 2001; Bunn and Arthington, 2002; Richter and others, 2003). Ecological processes affected by streamflow include succession; the transport and storage of sediments, nutrients, and organic material; connectivity of habitats in space and time; and biotic interactions (predator-prey, competition, invasive species, disease) (Naiman and others, 1988; Resh and others, 1988; Ward and Stanford, 1995; Ward and others, 2001; Bunn and Arthington, 2002; Nilsson and Svedmark, 2002). Ecotones (boundaries), edges, and tributaries are dominant features of river ecosystems and connectivity is easily disrupted because rivers and river networks are linear; branching features typically occupying the lowest areas in a landscape.

Although an assessment focused on ecological processes and conditions may better address the functions served by streamflow in river ecosystems than one based on historical or normative streamflow, its broad scope raises a number of issues. The assessment must account for many different and potentially important functions of streamflow in river ecosystems or provide a scheme for identifying the highest priority functions. There may not be information supporting precise streamflow requirements for any one function. Finally, disparate types of functions must evaluated using some common basis (for example, relative degree of impairment, consequences for fish populations).

To address these concerns, streamflow requirements can be targeted to specific taxa in river ecosystems (for example, Bovee, 1978; Gore and others, 2001), though a single-species focus presents the risk of neglecting potentially important ecological functions provided by streamflow and ground water. Puget Sound chinook salmon are important to many Tribes in western Washington as a fundamental part of their culture, a keystone species in the ecosystem, and an economic resource. Fish-based streamflow requirements may be based on evaluations of habitat suitability and availability using the toe-width method, instream flow incremental methodology (IFIM), limiting factor analyses such as Ecosystem Diagnosis and Treatment (EDT), or life-history models of fish populations (for example, Bartholow and others, 1993; Greene and Beechie, 2004). These approaches could be supplemented by approaches that address the fundamental role of streamflow in the creation and maintenance of aquatic habitats and streamflow requirements of other members of lotic communities.

Fish-based assessments can integrate the effects of many different ecological processes and biotic interactions, particularly if they evaluate those effects in terms of fish population size and structure. For example, the temporal and spatial connectivity within and between habitats and the variability of those habitats in space and time must be considered when assessing streamflow requirements either for fish populations or over the life cycle of individual fish. Some of the effects of streamflow on fish are indirect and depend on other factors such as their health, channel morphology, other species, or water quality. These indirect effects may be difficult to assess using an approach based strictly on the specific needs of fishes and, as a result, may not be sufficient to justify precise streamflow requirements. Processes operating over short time-scales that affect fish behavior (turbulence) or over long time-scales (catastrophic floods that create fluvial habitats and initiate succession) may be particularly difficult to evaluate in terms of fish-population responses but are, nonetheless, important for salmon (Reeves and others, 1995). Because of the number of fundamental information gaps in salmonid biology and river ecology (National Academy of Sciences, 1996; National Science and Technology Council, 2000), current models of salmon populations or river ecosystems do not comprehensively account for all potential functions of streamflow and, thus, may not be adequate to develop reliable streamflow requirements for rivers.

Components

Wild populations of harvestable salmon depend on water to support ecological functions in rivers that create and maintain habitats, provide connectivity between habitats, and regulate biotic interactions between salmon and their prey, predators, competitors, and diseases. The streamflow and ground water required to sustain salmon include an amount (or rate) needed for each function but also the quality of the water resources, their location in river networks, lakes, and estuaries, and the time when the water is present. The assessment of water requirements in western Washington, then, can be developed from three components: (1) the specific functions served by streamflow and ground water; (2) the locations and times where these functions occur, which would provide a basis for where and when water is needed in river networks, lakes, and estuaries; and (3) quantitative standards for the amount (rate) of water and its quality needed to support the each function in each location.

Quantitative water requirements for aquatic ecosystems are predicated on the specific needs for streamflow and ground-water discharge to rivers, lakes, and estuaries. Although water generally is necessary to maintain the ecological integrity of a river, it is difficult to ascribe a quantity or quality of water necessary for that general purpose. As a result, it may be useful to identify specific ecological functions of water in rivers, lakes, and estuaries that, in particular, affect salmon directly or indirectly at each stage of its life cycle. In many river basins, this would likely require distinguishing the requirements of different species or stocks, if only in terms of season when water is needed.

The ecological functions provided by water (table 2) vary by location in a river network. Likewise, the amount and quality of water required to maintain a given ecological function depends on both the function and the location of interest. Finally, many functions of water in aquatic ecosystems depend on spatial and temporal connectivity (for example, spawning units must be linked to marine water by continuous migration units, rearing units must be near spawning units, and streamflow must be continuous from periods of adult migration into streams through juvenile out migration). As a result, streamflow and ground-water requirements for ecological functions must be assessed comprehensively at the scale of individual habitat units throughout river networks, including lakes and estuaries, and hierarchically over a range of spatial and temporal scales.

Current and historical geomorphic processes and ecological functions of streamflow and ground-water discharge could be mapped for river networks, lakes, and estuaries in western Washington extending the "process domain" concept, developed by Montgomery (1999) to classify parts of river basin in terms of the dominant geomorphic processes that create and maintain habitat, to a broader set of ecological functions served by streamflow and ground water. The necessary conditions for each function could be identified from existing studies of river ecosystems and used to develop geographic criteria for the function. For a regional-scale assessment, the criteria would be expressed in terms of variables that can be derived from available regional geographic information (for example, slope, drainage area, channel width, channel confinement, riverbed material, channel forms/habitat units, land cover). The criteria could explicitly include spatial and temporal connectivity where a specific function at a specific location and time depends on conditions at another location or another time. The criteria would indicate whether a function was likely to occur at a given location or, if sufficient information was available, would be used to evaluate the function qualitatively or quantitatively. Rearing habitat for salmon could be mapped and evaluated qualitatively or quantitatively depending on the availability and quality of information about slow-water habitat, water temperature, cover, food resources, and predators. A mapping-based approach for evaluating the ecological functions of streamflow and ground water could be incorporated in a reach-impairment assessment currently being developed by NWIFC, but also would have to extend to estuaries in the nearshore where streamflow and ground water are vital for maintaining physical conditions, such as salinity gradients, and connectivity between marine and freshwater ecosystems.

The standards for establishing quantitative water requirements for ecosystems parallel the three types of approaches to setting streamflow requirements (historical, ecological, fish) discussed above. Historical streamflow provides a benchmark of flows that supported river ecosystems and viable populations of salmon. Historical streamflow conditions can be determined comprehensively for rivers and streams throughout western Washington by assessing historical water availability (see section, "Alternatives for Assessing Water Availability") and may serve as an interim standard of how much water is needed to support ecological functions.

A comprehensive assessment of historical streamflow would not just focus on the streamflow at a location in a river network. It would have an explicit spatial dimension to account for changes in channel network and channel morphology that affect habitat availability. For example, agricultural drains extend the channel network in basin but are not usable habitat for fish. Conversely, flood control practices reduce river length by straightening channels and isolating mainstems from side channels with levees. A historical flow standard can be refined with additional information including site-specific analysis to account for non-hydrologic changes.

Ecologically-based streamflow requirements still may be difficult to determine with passive investigations of river ecosystems because of the inability to control non-hydrologic factors and multiple functions that streamflow serves in rivers. In these cases, historical streamflow, single-species standards, or expert systems may be useful for defining streamflow requirements for fish while new investigations establish the sensitivity of ecological processes and conditions, including fish populations, to variation in streamflow patterns.

These approaches would have to be extended to ground water and other aquatic ecosystems, such as lakes and estuaries, for a comprehensive water-resources assessment in western Washington. As the roles of streamflow and ground water in aquatic ecosystems are identified and characterized, this information can be incorporated in models of fish populations (Bartholow and others, 1993) or ecosystem dynamics to develop comprehensive water requirements for aquatic ecosystems in western Washington.

Tasks

1. Identify functions of streamflow and ground water in rivers, lakes, and estuaries in rivers. Functions from one or more approaches (hydrologic, ecologic, fish) may be included in the assessment, which may range from a general need for historical flow patterns to specific needs such as a minimum depth to allow fish passage.

2. Map locations where streamflow and ground water historically supported each function and currently supports each function.

3. Develop standards (historical, ecological, habitat, fish population) for assessing whether there is sufficient streamflow and ground water of requisite quality to support each function. The standards may not be a function of water alone. For example, the streamflow required to maintain a given depth of flow depends on channel width. The standards would

include an explicit spatial dimension to account for non-hydrologic changes, such as structural modification of river channels and networks that affect habitat availability.

4. Develop quantitative requirements for the quantity and quality of streamflow and ground water needed for river ecosystems in western Washington based on existing methods and knowledge. Extend these methods to develop freshwater requirements for lakes and estuaries.

5. Initiate investigations of the sensitivity of ecological processes and conditions including fish populations to variation in streamflow patterns and develop tools to integrate hydro-ecological relations in the development of water requirements for rivers, lakes, and estuaries.

Regional Coordination for Implementing the Science Plan

The assessment of Tribal water resources in western Washington presents an opportunity for regional coordination in data collection, information systems, and technical analysis among: Tribes; Federal, State, and local government agencies; public and private utilities; and other water-resources managers. Regional coordination of these activities can increase their efficiency and the quality of their products. Assessment tasks based on regionally available data may be as easily implemented for the whole region as for specific sites. Water-resources managers will be able to address efficiently the full range of potential effects of proposed projects as well as to respond quickly to unanticipated projects with regionally comprehensive information either compiled or developed as part of the assessment. A regionally coordinated assessment can invest in evaluating and developing methods for interpolating or extrapolating information from existing data to areas where information is not available and apply these methods to the region. Regional coordination does not preclude, however, Tribes from pursuing distinct approaches that best fit their needs.

Regional coordination depends on consistent and reliable data collection and information management. At a minimum, data-collection methods must be documented. Standard procedures are necessary to assure the quality of data and to control for errors in instrumentation, methods, or data entry into information systems. Information systems are needed to store data that is accessible for use. By using compatible formats and common fields (for example, latitude, longitude, and time associated with data), Tribes and other agencies can readily share information. An information system can be designed to give users different levels of access to information depending on their needs.

Regional coordination will be important for addressing all types of information gaps. An approach for “down-scaling” information currently available at a coarse resolution (for example, rainfall) should be coordinated among organizations that would use the information. In basins where detailed information is lacking, all organizations involved in assessing water resources should be consulted to verify information gaps and to coordinate future monitoring and research.

Ultimately, the information needs of Tribal water-resources managers should guide implementation of the framework including the level of detail. The framework outlines some simple approaches for filling basic information gaps, particularly those related to water availability and water use at the basin scale, after an initial assessment of existing information. Detailed information about specific places will require more time and resources to address because of the vast spatial scope of the framework and the need for complex analyses to develop a thorough understanding of the availability of water resources, their uses, and their role in ecosystems throughout the region. Information needs of Tribal water-resources managers should be clearly linked to the specific products of any assessment–particularly as the assessment represents an increasing commitment of time and resources.

Regional coordination will be important to assess water requirements for aquatic ecosystems because of the need first to develop satisfactory methods for establishing the requirements and, then, to collect and analyze information for the assessment. In this case, concurrence about methods by Tribal and non-Tribal agencies in the region will be vital for broad acceptance of any results.

Regional coordination of a comprehensive water resources assessment provides the most efficient approach for compiling existing information and collecting new information to fill gaps. The steps outlined above will facilitate information sharing and regional-scale analyses of water resources. They also will promote the credibility of the assessment to the extent different organizations agree on common approaches for assessing water resources.

Tasks

1. Identify common water-resources data collected or monitored by Tribes and other water-resources managers to be shared or pooled for analysis.

2. Develop standard procedures for data collection, quality assurance/quality control, and data entry into information systems.

3. Identify or develop a system for sharing information about water resources in western Washington.

Summary

Management of Tribal water resources in western Washington depends on information about water availability, water use, and water requirements of ecosystems across the region. A comprehensive assessment of water resources in western Washington can provide Tribal water-resources managers with this information. The assessment encompasses many tasks including compiling existing data, monitoring water resources to address data gaps, analyzing information in ways that are useful to managers, and developing systems for organizing and accessing information. In some cases, available information and existing methods may be sufficient for some management decisions. In other cases, additional data collection and development of new methods may be required to address important issues facing managers. Ultimately, the information needs of resource managers should guide implementation of the framework including the level of detail.

The tasks do not have to be implemented uniformly across western Washington: different approaches could be used in different areas reflecting, for example, available information, varying Tribal water-resources policies, and distinct information needs by Tribal water-resources managers. The assessment could present many opportunities to coordinate efforts between Tribes and non-Tribal agencies to collect, analyze, and access information about water resources consistently and efficiently across the region. In this way, the comprehensive assessment of Tribal water resources can improve water management in the region and help target future monitoring and research in areas with the greatest uncertainties.

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